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Contracting for Infrastructure Projects as Credence Goods

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Abstract

Large infrastructure projects are a major responsibility of government, who usually lacks expertise to fully specify the demanded projects. Contractors, typically experts on such projects, advise of the needed design in their bids. Producing the right design is nevertheless costly.

We model the contracting for such infrastructure projects taking into account this credence goods feature and examine the performance of commonly used contracting methods. We show that when building costs are public information, multi-stage competitive bidding involving shortlisting of two contractors and contingent compensation of both contractors on design efforts outperforms sequential search and the traditional Design-and-Build approach. While the latter leads to minimum design effort, sequential search suffers from a commitment problem. If building costs are the private information of the contractors and are revealed to them after design cost is sunk, competitive bidding may involve sampling more than two contractors. The commitment problem under sequential search may be overcome by the procurer's incentive to search for low building cost if the design cost is sufficiently low. If this is the case, sequential search may outperform competitive bidding.

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1 Introduction

Contracting for large infrastructure projects, including public transportation, public services and utilities, and environmental restoration, is a main responsibility of urban and regional government. Such projects are typically complex and are beyond the expertise of the government, whereas contractors usually have the needed expertise. As a result, contracting for such projects involves eliciting from potential contractors information about the right design needed by the government. This is a typical feature of credence goods.[1]

In this article we take the credence goods feature of infrastructure projects into account and study how it affects the procurement process.

In an infrastructure project, the government's objective is two-fold: 1) eliciting from the contractors the right design which is costly to produce for the contractors; 2) finding a low price for the building of the project.

We set up a model capturing the essential feature of an infrastructure project that requires nontrivial design before it is built.[2] The government asks the contractors to formulate a design. The benefit to the government from contracting the project depends on the quality of the design and its building cost. Using this setup and assuming that building costs are public information, we examine the performance of commonly used contracting methods, including traditional Design-Build approach, multi-stage competitive bidding and sequential search.

A prevalent response to the issues of asymmetric information is the wide adoption of the Design-Build approach in public sector where the design and the build of a project are contracted to a single contractor. The contractor can either be selected through competitive bidding, sequential bargaining, or random draw. Under such an approach, the design phase is carried out after a contractor is selected and a price for building is fixed. Since the design effort is unobservable and the outcome of the project is nonverifiable, moral hazard problem is unavoidable and the resulting design effort by the selected contractor is minimal, echoing real world concern that Design-Build approach sacrifices quality and

[1] Credence goods refers to the type of goods or service where a buyer does not know the exact specification of the goods or service she needs while the supplier is able to determine this need. Besides infrastructure projects, medical services, repair services and various types of consulting and advisory services belong to this broad category. Darby and Karni (1973) first introduced the term 'credence goods' for these services. Dulleck and Kerschbamer (2006) provide a comprehensive survey of the research done on the topic.

[2] The model is adapted from Pesendorfer and Wolinsky (2003). They study solely sequential search while we examine the performance of several different procurement methods under different information structures.

design innovation. (See, for example, Akintoye and Fitzgerald (1995).)

We then consider a variation of the Design-Build approach which we refer to as "Multi-stage Competitive Bidding". Under this approach, several shortlisted contractors are asked to submit a design as well as a price for the building of the project. If the recommended designs of the contractors match, the government infers that the contractors have spent high design efforts and have come up with the right design. The project will be awarded to the one who has quoted the lowest price for the building of the project. All the shortlisted contractors will be reimbursed for their design effort. Shortlisting multiple contractors serves as a commitment tool for the government to elicit the right design, while rebating the shortlisted contractors for their design effort provides an incentive for them to choose high design effort. We find that multi-stage competitive bidding is almost socially efficient since two contractors are sampled, they choose high design effort and the right design is implemented at its marginal cost in equilibrium.

Another variation of the Design-Build approach we look at is "Sequential Search" where the government elicits sequentially a design and a price for building from each contractor. Under this approach, there does not exist an equilibrium where a contractor always chooses high design effort. The inefficiency comes from a commitment problem of the procurer. If all contractors exert high design effort, the procurer will not sample more than one contractor. However if the procurer always samples just one contractor, this contractor has no incentive to invest in design. In equilibrium, the procurer samples a second contractor with some probability as a disciplining device for the first sampled contractor, and all the sampled contractors randomize between high and low design effort in equilibrium. As a result, the right design is elicited and implemented with probability strictly less than one.

Among the three contracting approaches, multi-stage competitive bidding is the most efficient when building costs are public information or are private information of contractors but known before the effort in design is chosen. When a non-degenerate equilibrium exists, contractors always choose high design effort. As a result the right design is always produced and implemented, though at the cost of extra design effort and search cost. In comparison to sequential search, competitive bidding serves as a commitment tool to sampling multiple contractors, which forces contractors to choose high design effort with probability 1.

When the building costs are private information of the contractors and are revealed to them only after the design effort is sunk, it may be optimal for the government to shortlist more than two contractors under competitive bidding. If the design cost is sufficiently low, sequential search overcomes the commitment problem because the procurer has a high enough probability to always sample more than one contractor to achieve a low building price. In this case, sequential search may outperform competitive bidding because the optimal stopping price employed by the procurer under sequential search may be lower than the expected second lowest cost. Moreover, the ex ante expected number of contractors to be sampled may be lower for sequential search compared to the number of contractors shortlisted under competitive bidding.

In the remaining part of this section, we present the related literature. In Section 2, the model is presented. In Section 3, 4, 5, and 6, we analyze in sequence the equilibrium of Design-Build, multi-stage competitive bidding and sequential search and compare their performance under the assumption that building costs are public information. In Section 7, we examine the case that building costs are private information. Concluding remarks can be found in Section 8.

1.1 Related Literature

First of all, our paper is related to the literature on the management of infrastructure project contracting.[3] The complexity of infrastructure projects and the prevalence of asymmetric information between the procuring government and the contractors have been well acknowledged in the engineering world. Most papers on infrastructure procurement either take an empirical approach, by collecting data from projects implemented through Design-Build or other delivery methods, and analyzing the common factors that might be critical to the success of those methods (see, for example, Ndekugri and Turner (1994), Molenaar and Songer (1998), Molenaar, Songer, and Barash (1999), and EI Wardani, Messner, and Horman (2006)); or take a survey approach by collecting and summarizing interviewing results with experts (see, for example, Akintoye and Fitzgerald (1995)). Our paper complements this literature by formalizing an economic model capturing the key factors in infrastructure projects and carrying out a normative analysis on the several most important procurement methods.

Second, our paper relates to the literature on credence goods. Dulleck and Kerschbamer (2006) provide a comprehensive survey. Most contributions in that literature leave aside the costly design problem by either assuming costless design (see, for example,

[3] In economics literature, there is a large number of contributions on public sector procurement. For example, Vagstad (1985), de Silva, Dunne, Kankanamge, and Kosmopoulou (2008). These papers usually assume that the government understands perfectly the project to be procured, hence leaving aside the credence goods feature.

Pitchik and Schotter (1987) and Fong (2005)) or design effort is observable and a fair design fee can be imposed (see, for example, Wolinsky (1993), Wolinsky (1995), Emons (1997), Emons (2001), Alger and Salanié (2006)). Exceptions are Pesendorfer and Wolinsky (2003) and Dulleck and Kerschbamer (2009). Pesendorfer and Wolinsky (2003) study the case where design effort is costly and unobservable and contractors need to be incentivized to invest in design effort. Dulleck and Kerschbamer (2009) study the competition between experts that choose to exert effort and those that choose not to. Similar to Pesendorfer and Wolinsky (2003), we assume that the contractors' design effort is unobservable and costly and the final success of the service is not contractible. The main difference is that they analyze only sequential search assuming publicly known constant building cost, while we analyze the performance of three different methods under two different information structures. Adding to their work, we show that if building costs are public information, multi-stage competitive bidding with shortlisting and contingent design fees can serve as a welfare enhancing mechanism to incentivize contractors. On the other hand, if building costs are the private information of contractors, for sufficiently low design cost, the incentive of searching for a low building price can overcome the commitment problem. There we find a non-degenerate equilibrium under sequential search where contractors choose high design effort with probability 1. In that case, sequential search may outperform competitive bidding.

Third, our paper is related to the articles on auction theory that consider the usage of shortlisting to recruit firms as participants in an auction where shortlisted firms are reimbursed for bid preparation costs. In this literature the auctioneer invites potential suppliers to participate in competitive bidding over the design and subsequent supply of custom-made equipment. In that case, the auctioneer is interested in obtaining a low price but also wishes the experts to invest in design effort (see, for example, Laffont and Tirole (1993)). More recently, Kaplan and Sela (2006) study reimbursements in the framework of a second-price auction. Similar to us, Gal, Landsberger, and Nemirovski (2007) and Fan and Wolfstetter (2008) look at first-price auction. In these contributions, the contract to be auctioned does not have the feature of credence goods—the buyer knows perfectly the type of the service she needs. There, shortlisting is for the purpose of screening the contractors. Due to the credence goods feature, shortlisting has a very different function in our setup: it serves as a commitment device.

To our knowledge, our paper is the first to account for the credence goods feature in infrastructure contracting, the first paper studying competitive bidding in the procurement of credence goods and the first paper to examine the impact of asymmetric information under sequential search in the procurement of credence goods.

2 Description of the Model

The government wishes to develop an infrastructure project, but is uncertain about which design of the project is appropriate. The range of possible design is $[0, 1]$. The government benefits from the project a only if it matches her type $\alpha \in [0, 1]$. Her utility is

$$\begin{cases} V & \text{if} \quad \alpha = a; \\ 0 & \text{if} \quad \alpha \neq a, \end{cases}$$

where $V > 0$. The government does not know her own type α and has a uniform prior on $[0, 1]$. Thus, an unguided guess will not yield the right choice with a positive probability.[4]

There is an infinite population of identical contractors, indexed by $k \in \{1, 2, \cdots, +\infty\}$. Contractors serve a dual role: they recommend a design of the project to the government and, if chosen by the government, build the project according to the recommended design.

The design of the project is costly to produce for the contractors. For simplicity, the contractors must choose high or low design effort. High design effort leads to the correct design α. Low design effort leads to a random design drawn from a uniform distribution on $[0, 1]$.[5] The cost of high design effort is $c > 0$ and the cost of low design effort is zero.

For Sections 3, 4, 5, and 6, we assume that contractors are homogeneous in their cost to implement a design, and that cost is public information and is normalized to zero.[6]

[4]The important assumption for the analysis is that $V(a, \alpha)$ is a common value, i.e. independent of the contractor delivering the project. In a more elaborate model, the value of the implemented design would depend monotonically on its distance from the best design. Furthermore diagnosis may be be imperfect. But as long as there are common factors critical to the value of the service and their discovery depends on the efforts of the contractors in the same way, our analysis remains qualitatively the same.

[5]Note that the model does not leave the experts discretion over their recommendations: if the contractor invests high design effort he learns the true α, and the design he delivers has to be correct, otherwise, it has to be a random draw from a uniform distribution and the design will be wrong with certainty. This is for the purpose of avoiding uninteresting multiplicities in the communication between contractors and the government.

[6]The assumption made here is appropriate if building costs depend on the specificities of the project and are the same for all contractors (common value assumption). Our results remain qualitatively the same if contractors are heterogeneous in their building costs as long as they learn about their costs before deciding about design efforts—this may be an appropriate assumption for the case of building costs being dependent on the specificities of the contractors, for example experience. The analysis changes if contractors learn about their costs after deciding about design efforts—we consider this case in section 7.

The search cost of sampling each contractor is s. We assume $V \geq c+s$, i.e. in a first best case it is always efficient to build the project.

There are two sources of incentive problems: 1) the government can not not observe the contractors' design effort and hence can not be certain whether the design recommended by a particular contractor is the right one; and 2) the contractors have more information about the government's problem after the designing phase.

We refer to an equilibrium as *non-degenerate* if contractors choose high design effort with strictly positive probability, and an equilibrium as *degenerate* if all contractors choose low design efforts.[7]

We use the following definition of efficiency to evaluate the performance of a procurement method.

Definition 1. Efficiency *implies that only one contractor is sampled. That contractor spends high design effort and comes up with the right design. The right design is implemented at its marginal cost* 0*.*

3 Traditional Design-Build Approach

Design-Build is a widely used delivery system in public sector procurement projects. See, for example, Ndekugri and Turner (1994) and Molenaar and Songer (1998). There, a contractor is selected and the government procures design and building services from this selected contractor. The advantage of this approach is the easiness of coordination between design and implementation of design (building), since both jobs are carried out by the same contractor. As we see in the following remark, independent of the selection process of the contractor, Design-Build always leads to a serious moral hazard problem and is extremely inefficient in that the contractor's design effort is minimum.

Remark 1. *Under the Design-Build contracting approach, there only exists degenerate equilibrium where the selected contractor chooses low design effort.*

Suppose a contractor has been awarded a contract for design and building at price p, where p could have been determined either through competitive bidding or bilateral bargaining and the contractor has been determined through either random sampling, competitive bidding, sequential search, or some other selection approach. Recall that the design effort is not observable to the government. Given the contract, working out the right design leads to a final payoff $p-c$ for the contractor, while choosing low design effort

[7] The equilibrium concepts are borrowed from Pesendorfer and Wolinsky (2003).

brings him a higher payoff p. Hence there is no way that the procurer will find out that the contractor has shirked and provided a wrong design as the government does not have this information. The only equilibrium of the game is a degenerate one.[8]

The remark above is in line with the prevalent concerns in the engineering literature regarding the Design-Build contracting method - Design-Build sacrifices quality and design innovation (see, for example, Akintoye and Fitzgerald (1995).)[9] The economic driving force behind this is that, given a selected contractor, since design effort is unobservable and it is not verifiable by the government, and low design effort leads to a higher payoff for the contractor, since the high effort is more costly to the contractor while the price remains the same. As an alternative to Design-Build approach, the procurer may engage an architect to prepare the design before eliciting construction bids from contractors (Design-Bid-Build approach). This approach involves competitive bidding among contractors, but suffers from the same moral hazard problem if the government relies on one selected architect for the design of the project and design effort is non-verifiable.

4 Multi-stage Competitive Bidding

In this section, we consider a variation of the Design-Build approach, which we refer to as "multi-stage competitive bidding". The novel feature is that more than one contractor is sampled to produce a design and design effort costs are reimbursed contingently. The game proceeds as follows.

1. *Shortlisting Stage:* The government randomly samples n contractors from the contractor pool. The set of sampled contractors is denoted as $K = \{1, \cdots, n\}$. The government commits to use competitive bidding in awarding the building contract. She also commits to a contingent design fee d.

2. *Design Stage:* Sampled contractors simultaneously choose design effort $e_i \in \{0, 1\}$ and receive a signal α_i.[10]

[8]In practice there are ways that the moral hazard problem may be mitigated, for example, through reputation, certification of the architects, repeated interaction. Despite that, too little design effort is still a concern when Design-Build approach is used. (See, for example, Akintoye and Fitzgerald (1995).) Dulleck, Kerschbamer, and Sutter (2011) document experiments where experts' reputation does not help to increase market efficiency.

[9]In Wikipedia, it is reported that design and price selected through Design-Build approach arouses public suspicion and can lead to loss of public confidence. (See http://en.wikipedia.org/wiki/Design-build.)

[10]We do allow for mixed strategies in which case we denote by x_i the probability that a contractor

3. *Bidding Stage:* Each contractor submits a plan (a_i, p_i), where a_i is the design contractor i recommends and p_i is the price he charges for the implementation of that design.

4. *Building Stage:* The government learns about the plans. If $a_i = a_j$ for any $i, j \in K$, the contractors' designs match one another. The government chooses the contractor with the lowest price to build the project, and pays him the price he has quoted plus the design fee d. The losing contractors receive design fee d. Otherwise, the government quits the market without carrying out the project and no design fee is paid.[11]

The shortlisting stage is also referred to as the pre-qualification stage in contracting practice. As we have made the simplifying assumption that the contractors are homogeneous, any contractor is qualified for the project and random sampling satisfies the need of pre-qualification. The assumption that at the building stage the project is only implemented if all the contractors' designs coincide and that contractors are reimbursed only if the project is implemented, though a bit extreme, captures the casual observation that the government typically carries out a project only if advices on a project converge. If experts opinions diverge too much, a project is usually dropped or postponed. In this case, experts may not get reimbursed for their previous inputs. Reimbursing the design effort cost at the building stage corresponds to common practice of rebating bidding cost when the bid preparation is costly.

Suppose that the government is of type α and chooses design fee d. Use p_l to denote the lowest price from the competitive bidding. The government's payoff is:

$$\begin{cases} V - nd - p_l - ns & \text{if } a_i = a_j = a, \ \forall i, j \ \in K; \\ -nd - p_l - ns & \text{if } a_i = a_j \neq a, \ \forall i, j \in K; \\ -ns & \text{otherwise.} \end{cases}$$

A contractor i who has been sampled by the government receives the following payoff given his design effort $e_i \in \{0, 1\}$ and his strategy (a_i, p_i):

$$\begin{cases} d + p_i - e_i c & \text{if } a_i = a_j \text{ and } p_i \leq \min p_j, \ \forall j \in K, \ j \neq i; \\ d - e_i c & \text{if } a_i = a_j \text{ and } p_i > \min p_j, \ \forall j \in K, \ j \neq i; \\ -e_i c & \text{otherwise.} \end{cases}$$

chooses $e_i = 1$.

[11] The equilibrium outcome remains the same if the project is implemented as long as two contractors' designs match. But mathematical expressions become much more complex.

4.1 Equilibria and Efficiency

The strategy of the government is to choose the contingent design fee d and the number of shortlisted contractors K. The strategy of a sampled contractor i is a triple, (x_i, a_i, p_i), where x_i is the probability that contractor i chooses high design effort, a_i is the design he recommends, and p_i is the price he proposes for implementing the design a_i.

Remark 2. *There always exists a degenerate equilibrium where none of the shortlisted contractors chooses high design effort, that is $x_i = 0,\ i \in K$. Each player gets 0 payoff in such an equilibrium.*

At the design stage, the best response to other contractors' choice of zero design effort is zero design effort. Foreseeing that none of the contractors exerts high design effort, the government will not participate in the game. Hence everyone gets zero payoff from a degenerate equilibrium.

Nevertheless, it is more interesting to examine a non-degenerate equilibrium where contractors spend positive design effort and the right design is indeed produced and implemented with positive probability. Ideally one wishes for an equilibrium, where only one contractor spends high design effort, the right design is produced and the project is built at a low cost. However, as we show in the next remark, there exists no pure strategy equilibrium that leads to high design effort by one firm only.

Remark 3. *There does not exist any pure strategy equilibrium where one of the contractors chooses high design effort while the others choose low design effort.*

Given that the other sampled contractors choose low design effort, it is a best response for a contractor to choose low effort as well on being sampled. This excludes the possibility that full efficiency is achieved through the competitive bidding game stated above. Nevertheless, as we show in the following, when the cost of design effort and search is sufficiently low, full efficiency can be nearly implemented, but only at the expense of extra design effort and search cost. For this purpose we focus on the existence of an equilibrium where all the sampled contractors choose high design effort in the following analysis.

Lemma 1. *Suppose all the K sampled contractors have chosen high design efforts at the design stage, the equilibrium at the bidding stage is given by $(a_i, p_i) = (\alpha, 0)$ for any $i \in K$.*

Proof. Given that all the shortlisted contractors have chosen the high design effort at the design stage, suppose all the other contractors follow the recommended strategy of

$a_j = \alpha$. Contractor i, by recommending $a_i = \alpha$, may become the winner in the bidding game and receives some nonnegative price for building the project in addition to getting reimbursed the design fee d. By recommending otherwise, the designs will not match and contractor i gets 0 payoff. Hence recommending $a_i = \alpha$ is the best response for contractor i. Given $a_i = \alpha$ for all sampled contractors, it is a mutual best response to submit a bid which is equal to the marginal cost of implementing the recommended design, as in a standard Betrand competition. □

The next lemma shows that at the design stage, there indeed exists an equilibrium where all sampled contractors choose high design efforts if the design fee set by the government is sufficiently high.

Lemma 2. *It is a pure strategy equilibrium that all sampled contractors choose high design effort at the design stage where $d \geq c$.*

Proof. Given that the other contractors have chosen high design effort, choosing high design effort as well leads to a net payoff of $d - c \geq 0$, while choosing a low design effort leads to a payoff of 0. Therefore, choosing high design effort is a best response to the high design effort of the other contractors. □

Finally, one has to find out the optimal design fee for the government and the optimal number of shortlisting for the government. The purpose of the contingent design fee is to ensure that all the sampled contractors will participate in the game.

Proposition 1. *If $c + s \leq \frac{V}{2}$, there exists a non-degenerate equilibrium where the government shortlists two contractors and chooses the contingent design fee $d = c$. In this equilibrium (i) both shortlisted contractors participate in the game and choose high design effort. (ii) Each contractor submits a design that truthfully reveals the need of the government and a price that equals marginal cost of zero. (iii) Each contractor is chosen to implement the design with equal probability at the final building stage.*

Proof. Given the non-degenerate equilibrium of the game at the bidding stage, a contractor's profit from building the project is 0. His entire profit therefore comes from the design fee. A contractor's expected payoff from participating in the game is $-c + d$, expecting that he himself and his competitors will choose high design effort and their recommended designs will match. Hence, as long as $d \geq c$, the contractors' individual rationality constraints are satisfied and each of them is happy to participate in the game. Since the government's payoff is strictly decreasing in her payment to the contractors, the optimal design fee she will choose is $d = c$. Finally, since two contractors are sufficient to ensure a correct design and fully competitive bidding, the government will only sample two contractors if the total procurement cost does not exceed the value of the project, i.e. $V \geq 2(d+s)$. $\square$

Proposition 1 shows that $K = 2$ is the optimal number for shortlisting under public information. This is due to the simplifying assumption that a contractor produces the right design if he invests in high design effort. It may be optimal to shortlist more than two contractors if, after investing, each contractor comes up with a design that is a noisy estimate of the right one, or if contractors have private information about their building costs, as we will discuss in Section 7. At the bidding stage, since the contractors are homogeneous, two contractors are sufficient to drive the building price down to marginal cost, as in Betrand competition.

To coordinate on the non-degenerate equilibrium, the government with $c + s < V/2$ only needs to set the design fee marginally above c so that both contractors get strictly positive profit from participating in the game.

When the sum of search cost and design cost is too high ($c + s > V/2$), only the degenerate equilibrium exists. If this is the case, it is too costly to elicit the right design and the project is abandoned.

Proposition 2. *If $c+s \leq V/2$, the social loss of the multi-stage competitive bidding game is $c + s$.*

Proof. From Proposition 1, in the non-degenerate equilibrium, two shortlisted contractors spend high design effort, and the right design is produced and implemented at zero charge. Therefore, the only waste in comparison to the social welfare benchmark is the search cost for sampling one extra contractor and the design effort cost of one contractor. $\square$

When the design effort cost and search cost are sufficiently low in comparison to the value of the right project to the government, the social loss from the multi-stage competitive bidding game is negligible. Shortlisting two contractors and the contingent design fee together are sufficient to ensure that both sampled contractors participate in the game and both choose high design effort to produce the right design for the government.

5 Sequential Search

An alternative way of awarding the contract, instead of multi-stage competitive bidding, is sequential search. There, design and build are also awarded to the same contractor and multiple contractors may be requested to submit a design and a price for building. The crucial difference from competitive bidding is that contractors are sampled sequentially instead of simultaneously. As analyzed by Pesendorfer and Wolinsky (2003), the game involves an infinite number of discrete periods with each period unfolding as follows:

1. A contractor is chosen at random and offers a contract (d, p) where d is the design fee and p the price for implementing the design. If accepted, a contract requires the government to pay d to the contractor. In return, the contractor recommends a design and the government has the option to procure the project from the contractor at price p at any future date.

2. The government decides on one of the following actions: (i) accept the contract; (ii) sample a new contractor; (iii) procure the project from a contractor the government previously sampled; (iv) quit the project.

3. If the government accepts the contract, she pays the fee d and incurs a cost $s > 0$.

4. Next, the contractor chooses the design effort $e \in \{0, 1\}$. The contractor is allowed to randomize between the two effort levels with $x \in [0, 1]$, the probability of high design effort.

5. Finally, the contractor learns the design.

If the government engages in sequential search in awarding the contract, contractors never choose high design effort with probability 1.

Remark 4. *Under sequential search, there does not exist an equilibrium where a contractor chooses high design effort with probability* 1*.*

If the government only samples one contractor, the sampled contractor will choose low design effort, and the right design will not be produced. If the government instead samples two contractors in sequence, each contractor knows that the other contractor will or has been sampled, and will therefore choose high design effort. However, for the government, expecting that the first sampled contractor chooses high design effort, will not sample a second contractor. As a result, there does not exist an equilibrium where the government always samples more than one contractor and each sampled contractor chooses high design effort.

Under sequential search, as shown by Pesendorfer and Wolinsky (2003), when search cost s is sufficiently low and $c + \frac{s}{m} \leq \frac{V}{2}$ with $m \in (0, 1)$, there exists an equilibrium where the government samples a second contractor with positive probability strictly less than 1, and each sampled contractor chooses high design effort with positive probability strictly less than 1. The outcome of the equilibrium is that the right design is delivered with probability strictly less than 1.

6 Welfare Comparison

According to Definition 1, social efficiency requires that the right design be implemented if and only if $V \geq c + s$. As we see from previous analysis, for $V \in [c + s, 2(c + s))$, none of the three approaches is able to elicit high design effort from the contractors. Hence, none of the approaches achieves full efficiency.

For $V \geq 2(c + s)$, multi-stage competitive bidding has an equilibrium where sampled contractors choose high design effort for sure and the right design is produced and implemented. In comparison, the Design-Build approach always elicits low design effort, while sequential search elicits high design effort and the right design with positive probability less than 1 for a subset of $V \geq 2(c + s)$. Therefore, for $V \geq 2(c + s)$, multi-stage competitive bidding is superior to both Design-Build approach and sequential search.

Remark 5. *If $V \in [c+s, 2(c+s))$, none of the three contracting approaches elicits positive design effort from the contractors. If $V \geq 2(c + s)$, multi-stage competitive bidding is superior to Design-Build and sequential search.*

Under Design-Build approach, the moral hazard problem leads to low design effort. Under competitive bidding and sequential search, since the government uses multiple contractors to discipline the behavior of the contractors at the design stage, the moral hazard problem is mitigated.

Though solving partly the moral hazard problem, sequential search suffers from the critical drawback that the government can not commit to sample two contractors, which leads to the social inefficiency that though high design effort is chosen with positive probability, that probability is always less than 1. Under competitive bidding, this commitment problem disappears because competitive bidding itself serves as a commitment tool to use multiple contractors for design purpose. As a result, sequential search is inferior to competitive bidding as too little design effort is provided with the former.

From Proposition 2, the social cost of multi-stage competitive bidding is $c + s$, one extra design effort cost plus one extra search cost. When these costs are low and negligible, the competitive bidding approach is nearly efficient. Furthermore, the outcome from the competitive bidding is the second-best if the government's objective is to maximize her own net payoffs.

A side issue is whether competition improves welfare or not. Under sequential search, competition may be in conflict with good incentives for the contractors to choose high design effort, and imposing a floor on the price of building the project may be welfare-improving, as noted by Pesendorfer and Wolinsky (2003). Under competitive bidding, price competition helps the government to achieve the minimum cost in building the desired project. Therefore, whether competition improves social welfare or not depends critically on the underlining contracting approach. This suggests that competition itself may not be to blame for social inefficiency. Rather, how to harness competition and the ability to commit to a mechanism are the key in improving welfare.

7 Asymmetric Information

In this section, we relax the assumption that contractors are homogeneous in their building costs and examine the impact of asymmetric information. This is relevant if the projects are specific and contractors learn about their building costs when producing the design.[12]

Suppose $\gamma_i \in [0, \bar{\gamma}]$, firm i's building cost, is the private information of contractor i and is revealed to i after the design effort is sunk. Assume that observing own building cost is independent of design effort and is costless to a supplier. The underlying random variable Γ_i is identically and independently distributed according to a continuous and differentiable distribution function $G(\cdot)$, with density $g(\cdot)$. Suppose V is sufficiently large so that for every γ a non-degenerate equilibrium may exist under competitive bidding.

Besides the moral hazard problem, the Design-Build approach suffers from an extra drawback: the price that is fixed ex ante may not cover building cost. This will either lead to renegotiation of the building price of the project or a project being dropped as the contractor may suffer a loss and quit the project.

For multi-stage competitive bidding, suppose the procurer uses a second price auction instead of a first price auction so that truthful bidding is an equilibrium in (weakly) dominant strategies.[13] Different from our results in Section 4, the government may shortlist

[12] Another relevant setting is that contractors have heterogeneous costs which are largely determined by experience, i.e. known before the contractor's decision about design effort. This will not change the analysis presented above. See our discussion in Footnote 6.

[13] This replacement is purely for the purpose of easy exposition. Revenue equivalence holds in this setting. That is, given the same number of sampled contractors, the government's expected payoff from a first-price auction is identical to that of a second-price auction.

more than two contractors in equilibrium. For the government, shortlisting more contractors leads to higher total design and search costs, while having more contractors at the bidding stage leads to a lower expected building price. The trade-off between the costs and benefits for the government determines the optimal number of shortlisted contractors. As long as the benefit from sampling one extra contractor is larger than its cost $c+s$, the government will increase the number of shortlisted contractors.

Denote by $\Gamma^e_{(i:K)}$ as the the expected value of the ith lowest order statistic of K random variables, each distributed independently and identically according to $G(\cdot)$. K is the optimal number of contractors to be shortlisted if [14]

$$\Gamma^e_{(2:K-1)} - \Gamma^e_{(2:K)} \geq c+s, \quad \text{and} \quad \Gamma^e_{(2:K)} - \Gamma^e_{(2:K+1)} \leq c+s \tag{1}$$

are satisfied. In Condition (1), $\Gamma^e_{(2:K-1)} - \Gamma^e_{(2:K)}$ captures the expected decrease of the building price if K contractors instead of $K-1$ contractors participate in the bidding stage. We summarize the main findings in the following remark.

Remark 6. *When building costs are private information of the contractors and are revealed to them after design effort is sunk, it may be optimal for the government to sample more than two contractors.*

With asymmetric information, whether the commitment problem occurs under sequential search depends on the design costs. Under sequential search, the procurer determines an optimal stopping rule $\bar{p}$ for the building contract. If the building price quoted by a sampled contractor exceeds $\bar{p}$, the procurer samples the next contractor. If the quoted price is below $\bar{p}$, the procurer stops searching and procures the building of the project from that contractor. Suppose that any sampled contractor chooses high design effort with probability 1. Given any stopping rule $\bar{p}$ of the procurer, a contractor on being sampled infers that he is either the first contractor the procurer has sampled or all the previous sampled contractors have quoted a price above $\bar{p}$. Thus, he quotes a price above $\bar{p}$ if his marginal cost is above $\bar{p}$ and quotes a price equal to $\bar{p}$ if his marginal cost is below $\bar{p}$.

Consider an equilibrium where the equilibrium design fee is equal to its marginal cost c. The procurer chooses the optimal stopping rule $\bar{p}$ to minimize her expected total cost $\bar{p}+\frac{1}{G(\bar{p})}(c+s)$, where $\frac{1}{G(\bar{p})}$ is the number of contractors the procurer expects to sample until

[14]Note that $g_{(2:K)}(x)$, the density of the second lowest order statistic, is equal to $K(K-1)g(x)G(x)(1-G(x))^{K-2}$. First part of Condition (1) becomes $\int_0^{\bar{\gamma}} t(K-1)(K-2)g(t)G(t)(1-G(t))^{K-3}dt - \int_0^{\bar{\gamma}} t(K-1)Kg(t)G(t)(1-G(t))^{K-2}dt \geq c+s$.

she finds a contractor with a quote below $\bar{p}$. For uniform distribution on $[0, 1]$, $G(\bar{p}) = \bar{p}$ and the optimal stopping rule for the buyer is $\bar{p} = \sqrt{c+s}$. For the contractors, choosing high design effort leads to a payoff equal to

$$c - c + G(\bar{p})E[\bar{p} - \gamma \mid \gamma < \bar{p}] = \frac{1}{2}(c + s). \tag{2}$$

The third term on the LHS of (2) is a contractor's expected payoff on being sampled when he has a marginal building cost below $\bar{p}$ and expects to get the building contract at price equal to $\bar{p}$. Choosing low design effort leads to a payoff equal to

$$c + G(\bar{p})^2 E[\bar{p} - \gamma \mid \gamma < \bar{p}] = c + \frac{1}{2}(c + s)^{3/2} \tag{3}$$

for the contractor. The second term on the LHS of (3) is a contractor's expected payoff on being sampled when he is the first sampled contractor—the only event that he provides a wrong design and is not discovered and this occurs with probability $G(\bar{p})$—and at the same time has a marginal cost below $\bar{p}$. Contractors choose high design effort if and only if (2) is larger than (3). In a competitive equilibrium where the design fee is driven down to its marginal cost c, contractors will choose high design effort if and only if

$$s \geq c + (c + s)^{3/2}. \tag{4}$$

Note that in (4), LHS is constant with respect to c while RHS is an increasing function in c, and the inequality (4) holds when c is small and fails when c becomes sufficiently large. Therefore, there exists a $\bar{c}$ that satisfies

$$s = \bar{c} + (\bar{c} + s)^{3/2} \tag{5}$$

such that (4) holds if $c \leq \bar{c}$ and fails if $c > \bar{c}$.

Remark 7. *If building costs are the private information of the contractors and are revealed to them only after design effort is chosen, there exists non-degenerate equilibrium where sampled contractors always choose high design effort if the design cost is sufficiently low ($c \leq \bar{c}$). There the commitment issue in the case of complete information about building costs may be overcome by the procurer's incentive in search for low building costs. If the design cost is high, the commitment problem remains and sampled contractors choose high design effort with probability strictly less than* 1.

We conclude this section with a numerical example where under competitive bidding it is optimal for the procurer to sample more than two contractors and sequential search outperforms auctions for low design cost.

Example 1. *Suppose γ is uniformly distributed on $[0, 1]$, $c = 0.0225$ and $s = 0.04$. Under competitive bidding, sampling five contractors is optimal for the procurer. The total expected procurement cost for the procurer is* 0.645 *under competitive bidding. Under sequential search, the procurer sets a reservation price (stopping rule) equal to* 0.25 *and in expectation four contractors need to be sampled to get a quote below* 0.25*. The total expected procurement cost for the procurer under sequential search is* 0.5*.*

When the design cost is sufficiently low and commitment is not an issue, the optimal stopping rule under sequential search serves as a substitute for a reserve price under competitive bidding,[15] as the stopping rule optimally restricts the winning price below the second lowest cost. As a result, sequential search ensures a lower building price. Furthermore, in expectation, a smaller number of contractors is sampled to achieve a price below the stopping price. Therefore, sequential search outperforms auctions in Example 1. Moreover, in comparison to competitive bidding with reserve where the contract may not be awarded, sequential search with an optimal stopping rule "fails gracefully" — the procurer continues to search as long as the building price is not sufficiently low.

8 Conclusion

Contracting for large infrastructure projects is a major responsibility of government, who usually lack the expertise to specify fully the demanded project. Whereas contractors, typically experts on such projects, in their bids advise of the needed design of the project, while producing the right design is usually costly. This is a typical credence goods problem.

We have modeled the contracting for infrastructure projects taking such credence goods features into account and examined the performance of commonly used contracting methods, including the Design-Build approach, multi-stage competitive bidding, and sequential search. In our analysis the Design-Build approach always leads to low design effort. If building costs are public information, the multi-stage competitive bidding involving shortlisting of contractors, separation of design from bid and building of the project, and contingent compensation of multiple bidders on design efforts almost implements social efficiency. Shortlisting multiple contractors serves as a commitment tool for the government to use multiple contractors to elicit the right design, while rebating the shortlisted contractors for designing effort provides incentives for them to choose high

[15] For optimal auctions with reserve price, see for example Myerson (1981) and McAfee and McMillan (1987).

design effort. Under sequential search, the right design is produced and implemented with probability strictly less than one, because it suffers from a commitment problem of the government. Thus, when building costs are public information, multi-stage competitive bidding is superior to both sequential search and Design-Build.

If building costs are private information of the contractors and are revealed to them after design cost is sunk, it may be optimal for the government to sample more than two contractors under competitive bidding as the benefit from sampling more than two contractors for lower expected building price may dominate the extra search costs and design effort costs. Under sequential search, the incentive of the procurer to search for low building price may overcome the commitment problem if design cost is sufficiently low. In that case we find an equilibrium where contractors choose high design effort for sure and sequential search may outperform competitive bidding. This is because the procurer chooses a stopping price lower than the expected equilibrium price under competitive bidding and the expected number of contractors to be sampled is lower than the number of shortlisted contractors under competitive bidding.

A relevant issue we have not analyzed in this paper is that contractors may be heterogeneous in their design costs (or alternatively the contractors differ in their ability of producing quality designs). This would complicate the analysis as the firms that are more efficient in designing may have higher building costs. Furthermore, if contractors have both private information regarding design costs and building costs, screening arises both at the design stage and the building stage. This remains an interesting agenda for future research.

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